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Response of continental magmatic arcs to regional tectonic changes recorded by synorogenic plutons in the middle crust: An example from the Coast Mountains of British Columbia

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ABSTRACT

The Coast Mountains of British Columbia record an increase in magmatic activity, acceleration in exhumation rate, and a change from transpression to extension between ∼60 and 52 Ma. Structural analysis of fabrics in three mid-crustal plutons and country-rocks leads to conclusions about pluton emplacement mechanisms and strain partitioning during changing tectonic conditions. The Quottoon and Kitlope plutons (∼60 Ma) have steep foliations and lineations consistent with partitioned transpressional deformation. The Chief Matthew's pluton (∼57–55 Ma) intruded during the formation of a sub-horizontal transposition foliation, and has radially distributed lineations consistent with sub-vertical flattening during extension. The change in orientation of the foliation represents an almost orthogonal rotation of the shortening direction from sub-horizontal to sub-vertical. The Chief Mathew's pluton is interpreted to intrude initially into gently dipping fractures perpendicular to the steeply dipping foliation. These melt-filled fractures acted as conduits for melt, triggering horizontal flow, and eventually formed kilometer-scale sills. The steeply dipping fabrics of the Coast shear-zone provided pathways for melt to ascended from lower to middle-crustal depths. Partitioning deformation into three-dimensional domains of flattening, simple shear, and constrictional strain created the space for plutons. This pattern of deformation reflects the interaction of regional deformation with magma emplacement.

1. Introduction

The formation and emplacement of plutons is the principal mechanism by which continental crust differentiates and evolves (Paterson and Fowler, 1993; Brown and Solar, 1998; Petford et al., 2000). It is also one of the least understood geological processes because "pluton formation" cannot be directly observed. Laboratory experiments cannot simulate pluton emplacement because they lack the complexity of nature (Cruden, 1988; Paterson and Fowler, 1993); nor can they reproduce geological strain rates (Paterson and Fowler, 1993). Numerical models give insight into the problem, but make assumptions that may not be justified in nature (Bittner and Schmeling, 1995). Therefore, field observations of exhumed plutons are one of the best approaches to understanding the processes that control pluton emplacement.

Several studies have concluded that feedbacks occur between metamorphism, plutonism and deformation (Hollister, 1993; Karlstrom and Williams, 1993; Chardon, 2003; Andronicos et al., 2003; Klepeis et al., 2004). Pluton emplacement occurs in a variety of tectonic environments including convergent orogenic belts, raising the question of how space is made for plutons during contractional deformation. Many plutons have been correlated with shear-zones and regional scale deformation, pointing to a close association between deformation, pluton generation and emplacement (Hutton, 1987; Karlstrom, 1989; Kirby et al., 1995; Ingram and Hutton, 1994), although some have questioned this correlation (Paterson and Schmidt, 1999).

The Coast Mountains of British Columbia have proven to be an outstanding natural laboratory for the study of orogenic processes, including pluton emplacement (Hollister and Andronicos, 2006; Klepeis et al., 1998; Andronicos et al., 2003; Chardon et al., 1999; Chardon, 2003); interactions between deformation and plutonism (Hollister and Crawford, 1986; Ingram and Hutton, 1994); and plutonism and metamorphism (Hollister, 1982, 1993; Stowell and Goldberg, 1997; Stowell and Pike, 2000).

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This paper presents field studies of three plutons in the Coast plutonic complex of British Columbia, Canada (Fig. 1), that provide insight into the structure of a relatively unstudied segment of the Coast Mountains. Our analysis is focused on field relationships between the plutons and their country-rocks, the geometry of the plutons in relationship to the tectonic regime at the time of emplacement, and the role of shear-zones and preexisting structures in the emplacement of the magmas. Our results document the kinematic patterns that developed during plutonism and highlight the role of magma emplacement in controlling the architecture of the middle crust.

2. Tectonic overview of the Coast Mountains of British Columbia

The Coast Mountains are located on the western side of the Canadian Cordillera. The metamorphic and igneous rocks that constitute the orogenic belt today extend for more than a thousand kilometers along the North American margin. They track the tectonic evolution of an orogen from its formation by subduction and collision to its exhumation and uplift.

During the Mesozoic, a series of elongated terranes (e.g. Stikine, Wrangell and Alexander) collided along the western Canadian Cordillera (e.g. Monger et al., 1982; Johnston, 2001). The final terranes to collide compose the Insular Superterrane (Alexander, Wrangelia, and Taku terranes, and Gravina belt). The timing of the final docking of the terranes is still a subject of discussion, but most evidence points to assembly during the middle Cretaceous (Rubin and Saleeby, 1992; Crawford et al., 1987) followed by large magnitude right-lateral coast-parallel displacements (Irving et al., 1996; Enkin, 2006).

The localization of transpression from the amalgamation of terranes resulted in two orogen-parallel belts of high-grade metamorphic rocks and associated arc-related plutons, the Omineca and the Coast belts. The interior plateau of British Columbia separates the two belts. However, deformation, metamorphism, and plutonism across the Cordillera were synchronous (Struik, 1993; Johnston, 2001; Andronicos et al., 2003) suggesting tectonic linkage.

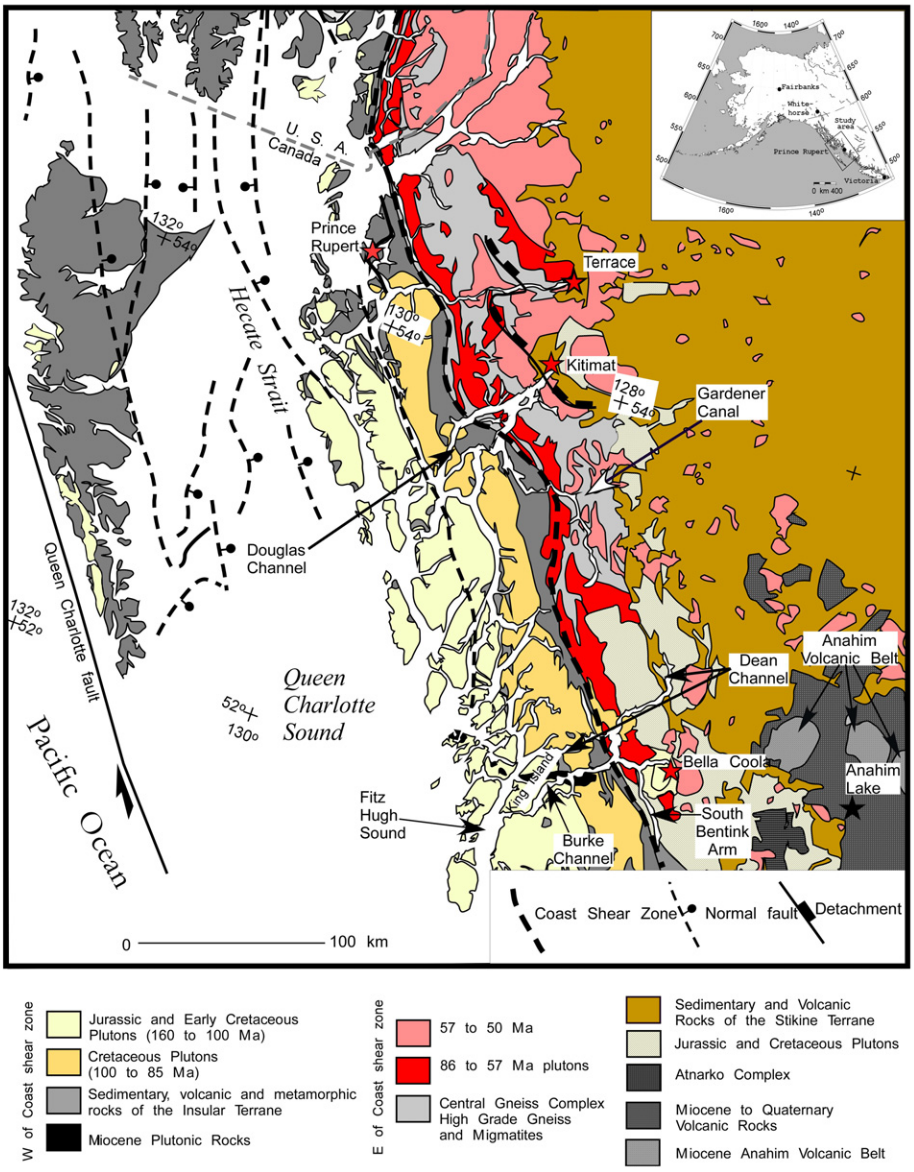

Fig. 1. Simplified geologic map of the Coast Mountains between 52° and 56°. Modified from Hollister and Andronicos (2006).

During the Late Cretaceous and early Tertiary (~90 Ma–~50 Ma), NW striking crustal scale dextral strike-slip faults segmented the Cordillera (Struik, 1993; Andronicos et al., 2003). These structures include the Tintina- Northern Rocky Mountain Trench and Pinchi faults along the eastern side of the Interior plateau, and the Fraser and Yalakolm faults in southern British Columbia (Gabrielse, 1985; Price and Carmichael, 1986; Struik, 1993; Umhoefer and Kleinspehn, 1995). The Coast shear-zone (CSZ) in the Coast belt has a complex kinematic history with right-lateral transpression (Andronicos et al., 1999; McClelland and Mattinson, 2000; Stowell and Hooper, 1990; Miller et al., 2000) followed by reverse and normal dip-slip displacements (Ingram and Hutton, 1994; Klepeis et al., 1998; Rusmore et al., 2005).

The crust was significantly thickened between 90 and 50 Ma (Hutchinson, 1982; Crawford et al., 1987; Thomas and Sinha, 1999; Hollister and Andronicos, 2006). In the Coast Mountains, magmatism and amphibolite to granulite grade metamorphism was focused east of the CSZ during this time interval (Hollister and Andronicos, 1997). At ~60 Ma the magmatic flux increased resulting in a magmatic flare-up that lasted until ~50 Ma, the most voluminous in the Cordillera (Hollister and Andronicos, 2006; Ducea and Barton, 2007; Gehrels et al., 2009). This event was accompanied by fast exhumation of several metamorphic core complexes within the Omineca belt (Struik, 1993; Parrish et al., 1988; Plint et al., 1992), and the Coast Mountains (Hollister, 1982, 1993; Andronicos et al., 2003).

The CSZ is the most prominent structure in the Coast Mountains. It separates rocks with contrasting magmatic, metamorphic and structural histories, and coincides with major topographic lineaments (Brew and Ford, 1978; Crawford and Hollister, 1982, Fig. 1).

The metamorphic rocks east of the CSZ that host the late Cretaceous and early Tertiary plutons are referred to as the central gneiss complex (CGC) (Hutchinson, 1982; Hollister and Andronicos, 2000, Fig. 1). The CGC is a high-grade metamorphic terrane and extends from southeastern Alaska to the Kitlope Lake (Fig. 1). It is characterized by peak temperatures >700 °C, peak pressures of >8 kbar, and a clockwise isothermal decompression P–T path. Biotite and hornblende cooling ages are <52 Ma (Hollister, 1982; Hollister and Andronicos, 2000; Andronicos et al., 2003; Rusmore et al., 2005). Upper amphibolite to granulite facies metamorphism occurred between the late Cretaceous and early Tertiary synchronous with plutonism (Andronicos et al., 2003; Johnston and Canil, 2007; Rusmore et al., 2005).

One of the most studied batholiths in the Coast Mountains is the Quottoon pluton, which is the southernmost occurrence of the orogen-parallel "Great tonalite sill" (Brew and Ford, 1981; Ingram and Hutton, 1994, Fig. 1), that extends from southeast Alaska to British Columbia. The CSZ occurs along the SW side of the tonalite sill for nearly 1200 km (Ingram and Hutton, 1994). The batholith is composed of physically and chemically distinct steep tabular plutons (Thomas and Sinha, 1999). Deformation within the CSZ was synchronous with crystallization of the tonalite sill (Ingram and Hutton, 1994).

The Gamsby Complex (Fig. 1) binds the CGC to the east, and its rocks likely form, in part, the protoliths for rocks of the CGC. Rocks at Mt. Gamsby record Jurassic deformation and superposition of three distinct deformation events (Hamblock, 2006). An early flat foliation associated with recumbent folds is overprinted by vertical NW–SE trending vertical folds that dominate the structure of Mt. Gamsby. The third deformation is linked to the intrusion of a tonalite at 155.3 Ma (Chang and Andronicos, 2009).

3. Structure of the southern termination of the Central Gneiss Complex

Gardner Canal provides access to a transect through the CGC and the associated plutonic bodies (Fig. 2). A regional map for the area was originally completed by Roddick (1970) as part of the Coast Mountains mapping project. Our work is based on detailed mapping of a ~40 km transect from Europa Reach to Queen Point and of the ranges flanking Kitlope Lake, which is located SW of Gardner Canal (Fig. 2).

The country-rocks of the plutons at Gardner Canal and Kitlope Lake are upper amphibolite facies orthogneiss and amphibolite interlayered with rare paragneiss. Pegmatite and aplite dikes that intruded prior to the last deformation phase typically crosscut these rocks. The layers of paragneiss are easily recognized in the field by their rusty weathering. Calc-silicate rocks also occur in the area and are green in color due to the abundance of epidote and diopside.

The three main plutonic bodies in the area are: 1) An NW–SE granodiorite correlated with the Quottoon pluton; 2) a granodiorite SE of the Quottoon pluton named here as the Chief Matthew's Pluton; and 3) a granodiorite called the Kitlope Pluton further to the south (Fig. 2). Nine localities have radiometric zircon ages in the area (Gehrels et al., 2009). One zircon age for the Quottoon pluton is 59.5 ± 1.6 Ma. Two ages for the Chief Matthew's pluton are 55.6 ± 0.9 and 58.2 ± 0.9 Ma. The Kitlope Pluton has an age of 61.1 ± 1.2 Ma. The other two ages are of orthogneiss of the central gneiss complex and are 96.8 ± 2.1 and 125.4 ± 3.3 Ma. The final three ages date the Gamsby complex, and are a quartz diorite of 188.1 ± 3.3 Ma, a tonalite of 155.3 ± 2.7 Ma, and a younger dike of 52 ± 2.8 Ma (Chang and Andronicos, 2009). Even though the average age difference between the Quottoon, Kitlope, and Chief Matthew's plutons is only ~6 Ma, the geometry and kinematics of the structures associated with individual intrusions are distinct.

3.1. *Kitlope Pluton (~61 Ma) and country-rocks*

The Kitlope pluton is a granodiorite that has a nearly vertical northern contact that strikes E–W (Figs. 2 and 3). The intrusion consists of discrete sheets of granodiorite separated by (rare) screens of orthogneiss and amphibolite. Many regions within the granodiorite sheets preserve pristine magmatic textures.

The plutonic fabric varies from a magmatic foliation with a solid-state overprint (S_K) to non-foliated (symbols compiled in Table 1). The strongest solid-state foliations occur near the contacts and near country-rock screens. The foliation is sometimes concordant with country-rock fabrics, but in some locations it crosscuts. Foliations in the mountains east of Kitlope Lake strike E–W with consistent steep to sub-vertical dips (Fig. 3). Foliations west of the lake strike on average N–S with steep west dips. These foliations are folded across axial planes that strike E–W (see below).

Mineral lineations (L_K) within the pluton are mainly defined by hornblende. On the west side of Kitlope Lake, mineral lineation orientations in the pluton and country-rocks are variable, but generally plunge steeply (Fig. 3). On the east side of Kitlope Lake, at Mt. Blane, the lineations define a weak girdle sub-parallel to the foliation plane, with a west plunging maxima (Fig. 3).

The ridges west of the Kitlope Lake show a foliation folded into open folds defined by screens of country-rocks. These folds (F_K) have steeply plunging hinges sub-parallel to the mineral lineation. The approximate orientation for the fold axial plane is E–W, which is consistent with the general E–W striking foliation seen in the pluton at Mt. Blane to the east, and N–S shortening and vertical stretching.

The northern contact of the pluton on the west side of Kitlope Lake is defined by an intrusive breccia, composed of two phases of the Kitlope pluton (Fig. 4a). The country-rocks north of the breccia have an NW striking foliation. South of the breccia, the foliation in the pluton strikes ~E–W with steep dips similar to the orientations to the east at Mt. Blane. In contrast, the northern contact at

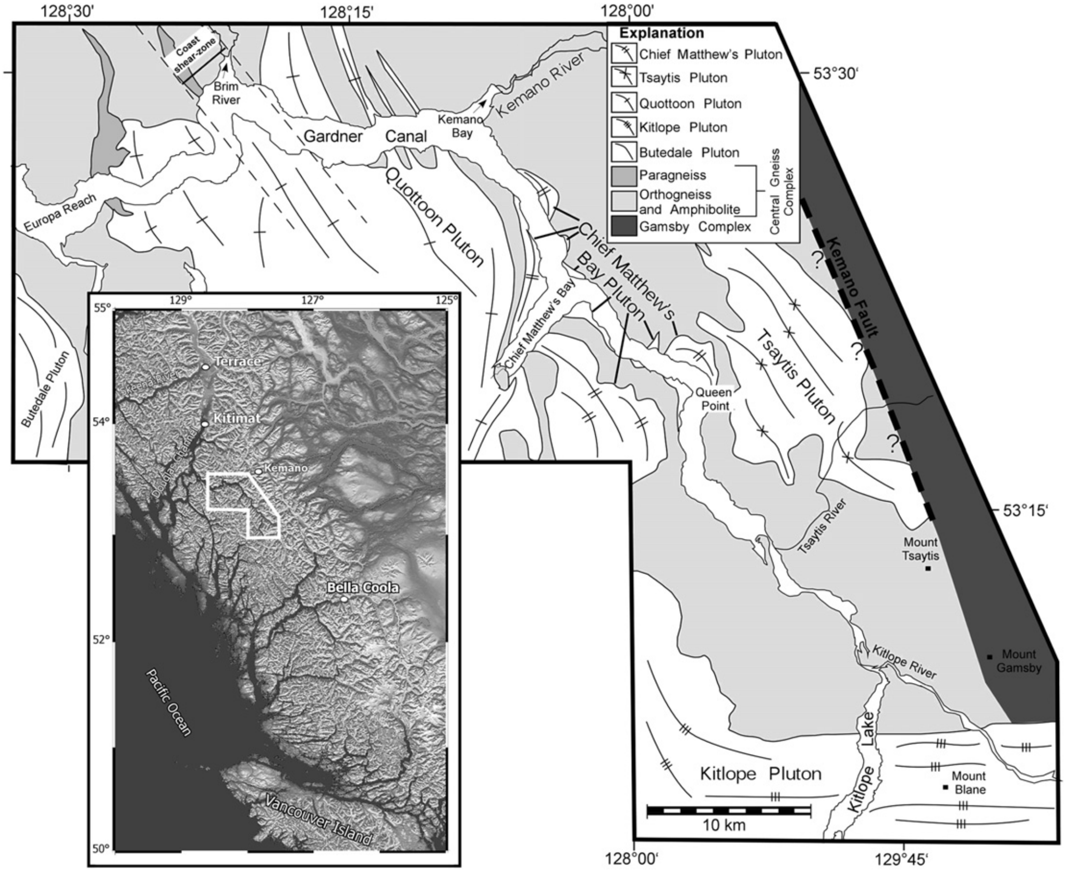

Fig. 2. Geologic map of study area. The map shows geographic locations, major plutons and distribution of major rock types. Location of Kemano Fault is inferred by (Van der Heyden, 1989). Inset shows shaded relief map of Coast Mountains and towns outside of study area.

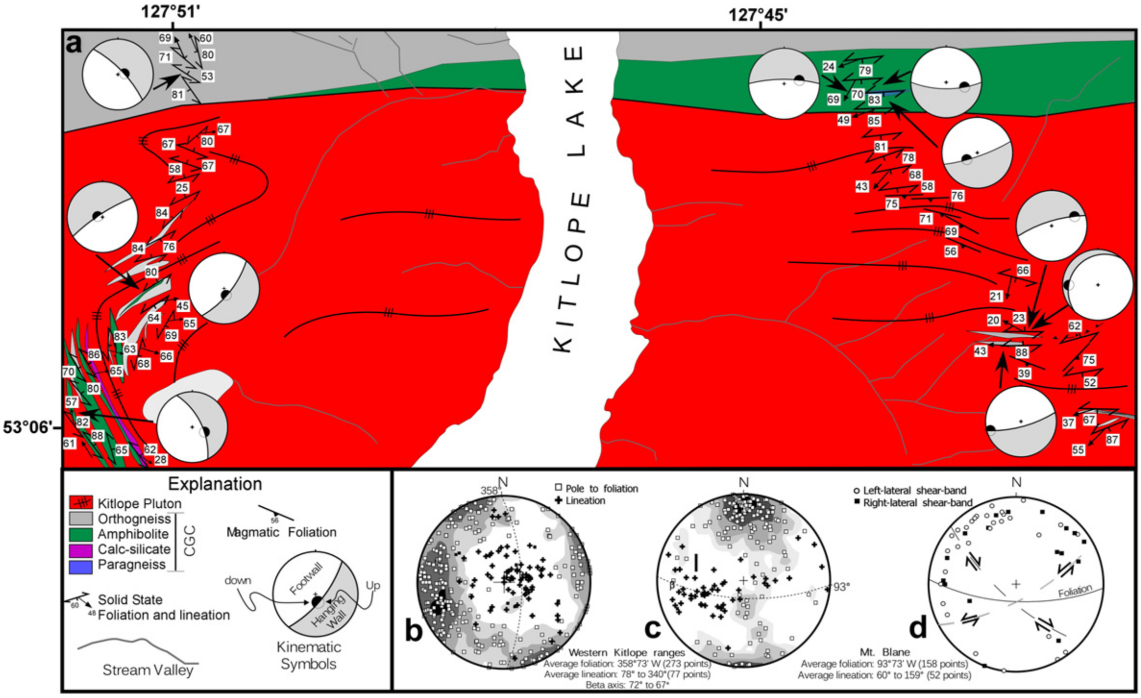

Fig. 3. Geologic map and stereographic projections summarizing the structure of the Kitlope Lake area. a) Geological map and stereonets. Arrows point to locations where kinematic observations were made. b) Stereonet of foliation and lineation in the western Kitlope Ranges. Contours are two percent. c) Stereonet showing foliation and lineation for the Mount Blane area, east of Kitlope Lake. Contours are two percent. d) Stereonet summarizing shear-bands in Mount Blane area. The mean foliation, right-lateral and left-lateral shear-bands are plotted as great circles.

Table 1
Deformation events.

Event	Location		Associated structures	Intrusion	Regime	Time
D1	Gardner Canal		Steep and flat fabrics Boudinage			$>$125 Ma
D2	From Brim River to South of Kemano Bay	S_2	NW–SE foliation steeply dipping to the SW	Quottoon Pluton	Horizontal flattening	$\sim$60 Ma
		F_2	folds with axial planes//to S2			
		L_2	Lineation radially distributed			
			Top to the NE reverse shear			
	Kitlope Lake	S_k	$\sim$Vertical E-W foliation	Kitlope Pluton		
		L_k	$\sim$Vertical lineation			
		F_k	folds with E-W axial plane			
	Europa Reach	S_{ER}	Steep NW–SE foliation			
		L_{ER}	S-plunging shallow lineation			
			dextral shear-sense			
D3	From South of Kemano Bay to South of Queen Point including Chief Matthew's Bay	S_3	NW–SE foliation shallowly dipping to the SW	Chief Matthew's Pluton	Subvertical Flattening	$\sim$58 Ma
		L_3	Lineation radially distributed in foliation plane with 2 orthogonal maxima			

Mt. Blane is sharp, steeply dipping and concordant between the country-rocks and the pluton. Parallel to this east-west striking contact the pluton has well developed solid-state foliation that decreases in intensity to a magmatic alignment of feldspar in the interior of the pluton. This transition occurs within 500 m of the contact.

3.1.1. *Kinematics*

At Mt. Blane, shear-bands were the most common kinematic indicator (Fig. 4b). Two populations of strike-slip shear-bands were recognized with a conjugate geometry. In stereographic projection, the acute angle made by the intersection of right-lateral and left-later shear-bands is bisected by the average foliation plane (Fig. 3). This observation is consistent with formation of the shear-bands at the same time as the formation of the foliation. The geometry is consistent with N–S shortening perpendicular to the plutonic contact. A larger number of left-lateral shear-bands suggest left-lateral shear predominated.

At the micro-scale, kinematic indicators show S-side up shear within the pluton and country-rock screens. Outcrop-scale asymmetric folds within the country-rocks at the northern contact of the pluton are also consistent with S (pluton) side up shear. The folds and kinematic indicators are both consistent with the pluton moving up relative to the country-rocks at its northern contact (Fig. 3).

3.2. *Quottoon pluton ($\sim$60 Ma) and country-rocks*

In the study area, the Quottoon pluton occurs between Brim River and Kemano Bay. The pluton is a granodiorite characterized by interleaved tabular plutonic bodies with steep dips and abundant country-rock screens. The number of country-rock screens increases toward the eastern contact at Kemano Bay (Figs. 5 and 6). Migmatites are common within the country-rock screens east of Brim River. Patches of felsic minerals and course-grained hornblende with igneous textures are characteristic. The migmatites are texturally and mineralogically similar to migmatites found near the Skeena River to the N (Kenah and Hollister, 1983; Lappin and Hollister, 1980). Many of the patches are present as tabular gashes at high angles to the stretching lineation in the rock, suggesting they originated as melt-filled tensile fractures (Fig. 4c).

The country-rocks that host the Quottoon Pluton are folded and contain evidence for at least two episodes of deformation (Table 1). The eastern margin of the Quottoon pluton presents asymmetric NE vergent folds (F_2). The axial planes to the folds dip steeply to the SW with shallowly plunging NW–SE trending hinges. The folds become tighter toward the west. The folds deform an earlier gneissic foliation (S_1) characterized by shallow dips. The older fabric (D_1) contained extensive boudins as indicated by folded boudins in the area between Brim River and Kemano Bay (Fig. 4d). The boudin necks were reactivated during F_2 folding into reverse, top-to-the-NE leucosome filled shear-bands. At the contact the of the Quottoon pluton, cuspate/lobate folds occur with the cusps into the pluton demonstrating the pluton was partially molten during folding. The axial planar cleavage to these folds (S_2) dips SW, subparallel to the shear-bands.

A well-developed mineral lineation (L_2) is defined by aligned hornblende. The lineation forms a girdle distribution parallel to the S_2 foliation plane (Fig. 6a and d). Several outcrops contain such a strong lineation that it was difficult to measure a foliation. These domains of strong linear fabric were found at the fold hinges within the country-rocks, and within a mylonitized section of the Quottoon pluton. The stretching direction of boudins also occur parallel to the axes of F_2 folds. These observations indicate stretching parallel to the fold axis during F_2 at the macroscale. However, the distribution of stretching lineation on a girdle parallel to S_2 is consistent with flattening at the bulk scale (e.g. Gapais et al., 1987).

Across the CSZ, the Quottoon pluton contains a single well-developed foliation that strikes NW–SE with steep western dips (Fig. 6), parallel to the axial planar cleavage within the country-rocks to the east, suggesting a synchronous formation of the two structures. The foliation within the pluton is defined by the alignment of biotite, hornblende and tabular plagioclase grains. Microscopically, the fabric is defined by aligned laths of plagioclase and interlobate grain boundaries with bulging microtexture (Fig. 4e). Chessboard extinction in quartz is widespread. Plagioclase also contains abundant mechanical twins, some of which are bent. These textures are consistent with deformation at temperatures close to the solidus of the rock, and are similar to those described for the Quottoon pluton farther north (Ingram and Hutton, 1994; Andronicos et al., 1999).

A spatial change in deformation behavior across the pluton is indicated by an increase in the intensity of fabrics and changes in microstructures. For instance, in the west, quartz fills cracks in plagioclase. Quartz grains within the crack fillings have core and mantle microstructure, typical of deformation in regime 2 of Hirth and Tullis (1992). The cracks are oriented perpendicular to the lineation within the rock and are associated with the presence of sericite and epidote, consistent with alteration in the presence of fluids. These microstructures contrast with those in more eastern samples that show no evidence for brittle deformation or alteration

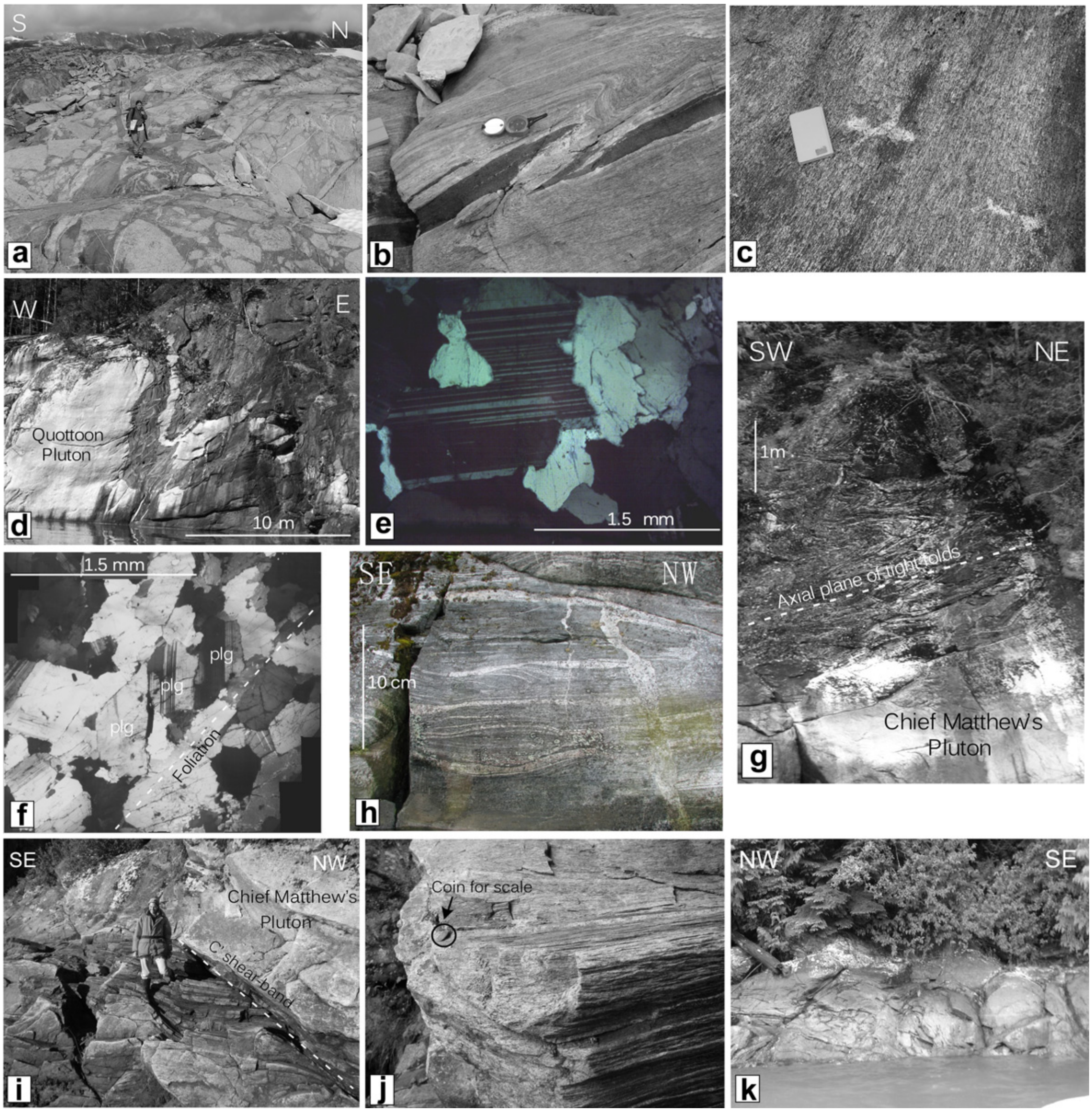

Fig. 4. Mesoscale and micro-scale pictures of structures found in the study area. (a) Agmatite breccia located at the contact of the Kitlope pluton with the country-rocks to the north, in the western Kitlope Lake ranges. (b) Reverse shear-band in the Kitlope pluton cutting mafic dike with asymmetric fold of host rock fabric. The shear-band contains leucosome interpreted to indicate melt present during shearing. (c) Leucosome-filled tension gashes perpendicular to the steeply dipping foliation of the Quottoon pluton. (d) Folded amphibolite at locality 2. Note that boudins within the amphibolite are folded across the fold and the necks of the boudins form reverse shear-bands. Asymmetry of folds and shear-bands indicates top to the NE shear. Light colored material in boudin necks is leucosome interpreted to represent partial melt filling boudin necks. (e) Photomicrograph of sample of Quottoon Pluton showing plagioclase with mechanical twinning and bulging boundaries at quartz-plagioclase grain boundaries. Also note interlobate grain-boundary between quartz grains. (f) Photomicrograph of tiled plagioclase. (g) Tight to isoclinal folds in amphibolite at the contact with the Chief Matthew's pluton at locality 3. The axial plane of the folds is parallel to the intrusive contact. (h) Country-rock at the base of the Chief Matthew's pluton. The horizontal foliation is boudinaged, with leucosome parallel to the foliation and filling boudin necks. (i) NW-dipping shear-bands in amphibolite at the bottom contact of the Chief Matthew's pluton at locality 5. (j) L-tectonite in orthogneiss at locality 5. (k) Macrocale chocolate-tablet boudinage in country-rock at locality 6.

in the presence of fluids. This change in microstructure from higher temperature in the east, to lower in the west indicates that deformation is associated with a decrease in temperature across the pluton, and an east to west thermal gradient across the CGC (Wood et al., 1991). Similar textures and structures that document decreasing temperatures during deformation were interpreted by Ingram and Hutton (1994) to indicate that deformation occurred as the pluton solidified.

3.2.1. *Kinematics*

We used the asymmetry of F_2 folds to infer map-scale fold vergence. The fold asymmetry indicates NE vergence. At Brim River (Locality 1, Figs. 5 and 6), a series of folded pre-tectonic pegmatitic dikes also have asymmetry consistent with NE vergence (Fig. 6). The NE vergence of the folds is confirmed by reactivated boudin necks (Locality 2, Figs. 4d–5) that form top-to-the NE reverse shear-bands synthetic with the F_2 fold vergence.

3.3. *Chief Matthew's pluton (~57 Ma) and country-rocks*

The Chief Matthew's pluton is a gently dipping tabular pluton that extends from south of Kemano bay to Queen Point, including Chief Matthew's Bay (Figs. 2–5). The pluton consists of several discrete granodiorite sills that together account for a thickness of ~6 km (Fig. 7). The pluton contains hornblende and biotite as mafic minerals. However, sectors of the pluton are more felsic and are

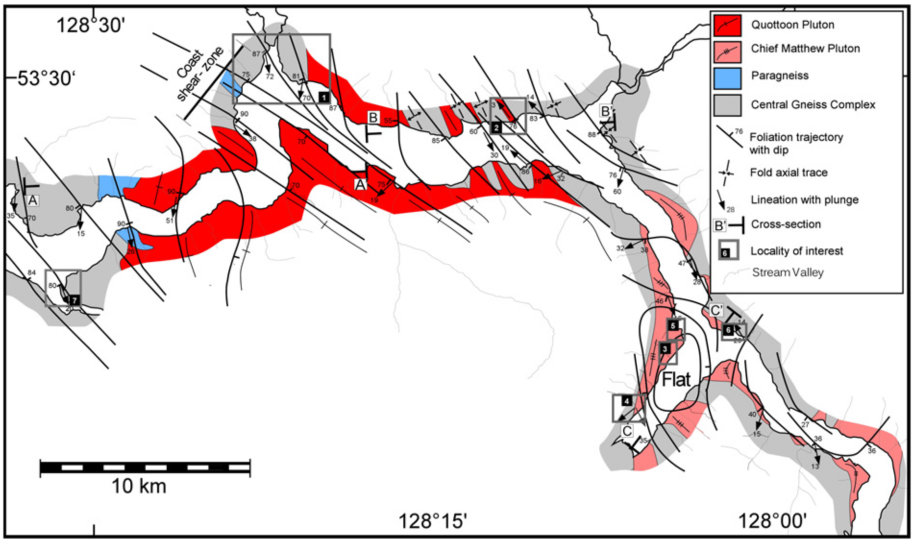

Fig. 5. Simplified geological map of Gardner Canal from our mapping and the map of Roddick (1970). Field measurements were interpolated to produce foliation trajectory maps. Locations discussed in text are shown.

characterized by the absence of hornblende and the presence of grains of microcline up to 2.5 cm in length.

At the microscopic scale, plagioclase is subhedral with tabular shape. Grains are normally zoned and twinned. Quartz is anhedral and located in the interstices of other minerals indicating that it formed late in the crystallization sequence. Biotite is subhedral and has a pleochroism that varies from yellow to dark brown. Hornblende is subhedral and associated with biotite and titanite. K-feldspar is not very abundant, except in the hornblende absent sectors mentioned above.

The pluton has both magmatic and solid-state foliations. Modifications to the original magmatic texture of the rock are obvious in quartz, which has chessboard extinction, bulging edges, and subgrains. Feldspar has a relatively pristine igneous texture with only deformation twinning. However, plagioclase grains are imbricated (Fig. 4f). Shear-bands are widespread in outcrop and thin section. Solid-state deformation is not widespread throughout the pluton and is most common near the margins of the sills. The magmatic foliation within the pluton parallels foliations in the country-rocks. Throughout the sill complex foliations strike NW–SE and dip gently SW (Fig. 7).

In the country-rocks, a new foliation (S_3) is developed that overprints S_1 and S_2 (Table 1). This foliation is associated with F_3 folds that are tight to isoclinal with axial planes parallel to the contacts with the sills (Locality 3, Figs. 4d–5). The S_3 fabric is associated with intense boudinage and complete transposition of S_2 fabrics. The boudin necks are filled with granodiorite indicating that the deformation occurred as the sills intruded. The F_3 folds occur at the pluton/country-rock contact (Fig. 4g). Melt related to the intrusion of the pluton crosscuts and parallels the flat foliation S_1 (Fig. 4h). We interpret this relationship as the Chief Matthew's pluton reusing and reactivating S_1 while intruding.

The lineation (L_3) is best developed in the country-rocks and is defined by alignment of hornblende, elongate mafic enclaves, and tabular feldspars. Two different, nearly perpendicular lineations occur. The most common lineation trends NW–SE and plunges

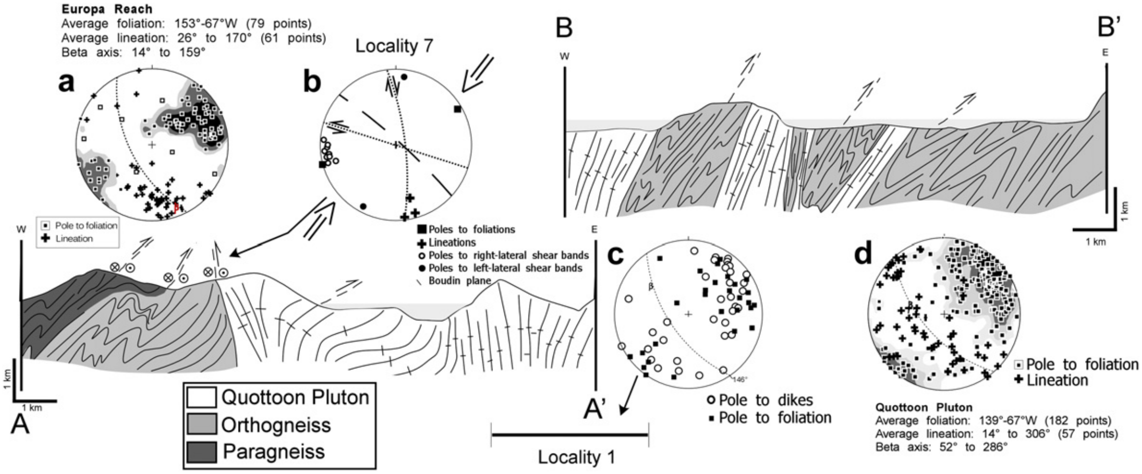

Fig. 6. Cross-sections A to A′ and B to B′ (see location in Fig. 5) showing geometry of structures across the CSZ between Europa Reach and Brim River. a) Lower hemisphere, equal area stereonets showing poles to foliation and lineations for rocks at Europa Reach. b) Stereonet showing geometry of conjugate strike-slip shear-bands. c) Poles to foliation and dikes within the Quottoon pluton. d) Poles to foliation and lineations within the Quottoon pluton near Brim River.

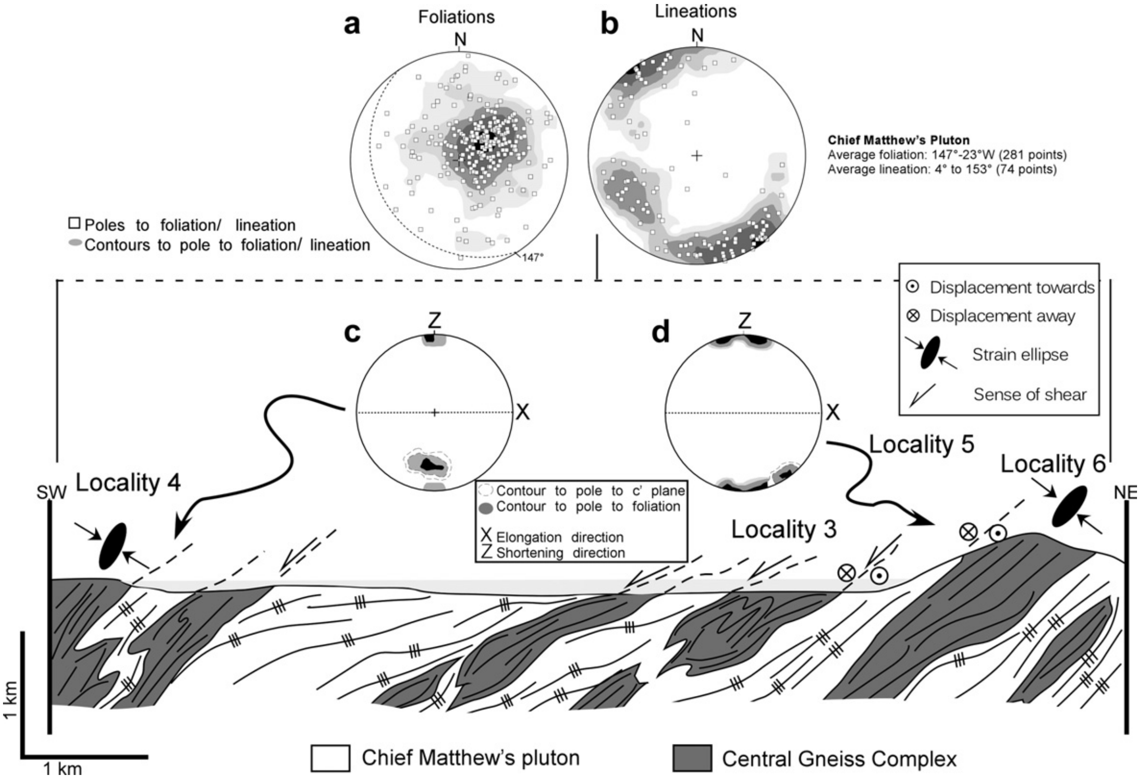

Fig. 7. Cross-section C to C′ (see location in Fig. 5) illustrating structure across Chief Matthew's Bay. a) Lower hemisphere, equal area stereonet of poles to foliation for the Chief Matthew's pluton, average foliation is plotted as a dashed great circle. b) Stereonet of lineations within Chief Matthew's pluton. c) Stereonet of shear-bands at locality 4 rotated so that the average foliation is E–W and vertical and lineation is horizontal and E–W (kinematic reference frame). d) Stereonet of shear-bands at locality 3 rotated so that the average foliation is E–W and vertical and lineation is horizontal and E–W (kinematic reference frame).

shallowly. The second lineation is present within the plane of shear-bands, and plunges moderately to shallowly to the SW. The two lineations together define a girdle distribution parallel to the mean foliation plane within the sill complex (Fig. 7).

3.3.1. *Kinematics*

The two most common kinematic indicators within the Chief Matthew's pluton are asymmetric shear-bands (C′) at the macroscale, and asymmetrically tiled feldspars at the microscopic scale (Fig. 4f).

At the southern tip of the Chief Matthew's Bay, the top of the Chief Mathew's pluton is exposed (Locality 4, Figs. 5–7). The shear-bands in this area strike NW–SE and dip ∼30° to the SW. The shear-sense across the bands is top down to the SW. The lineations within the shear-bands plunge to the SW while the lineation within the foliation plunges to the NW. The geometry of the shear-bands coupled with the lineation and foliation indicate two directions of stretching. Mutually crosscutting relationships show that deformation was synchronous with plutonism at this location and that both stretching directions developed during plutonism. For instance, an apophysis of the pluton crosscuts the foliation, but is also folded across an axial surface parallel to the local foliation. Furthermore, the shear-bands offset the apophysis of granite and also have granitic material concentrated into the shear plane. These relationships indicate that granite intrusion occurred during foliation development and folding as well as shear-band development.

Along the NE side of Chief Mathew's bay, near its intersection with Gardner Canal (Locality 5, Figs. 5–7), the bottom sill is exposed. Shear-bands in this area strike NE and dip to the NW. The sense of shear is top-down to the NW. The contact between the country-rocks and the pluton is concordant with both the shear-bands and the foliation (Fig. 4i). In this case, the intersection of the foliation plane and the shear-bands is normal to the stretching lineation, indicating that the foliation and shear-bands are kinematically compatible (Passchier and Trouw, 1996). The shear-bands have a monoclinic symmetry consistent with non-coaxial deformation (Fig. 7). L-tectonites are also found in this area, and their lineation plunges parallel to the lineation found in L-S tectonites, which are cut by the shear-bands (Fig. 4j). The geometry of the shear-bands and L-tectonites suggests top-to-the NW directed non-coaxial shearing along this contact of the pluton. The shallow fabrics and normal shear-bands are consistent with horizontal extension and sub-vertical shortening.

On the northeastern side of Gardner Canal opposite Chief Mathew's Bay, the base of the sill complex is exposed (Locality 6, Fig. 5). In this area, shear-bands form anastomosing networks that interlink to form chocolate-tablet boudinage of the gently dipping S_3 foliation (Fig. 4k). The geometry of the shear-bands and boudins suggests a large coaxial component to the deformation. Since the average lineation and enveloping surface of the boudins are gently dipping, the shortening direction is inferred to be sub-vertical in this area. This inference is confirmed by the presence of extensive dike and vein arrays with mutually crosscutting relationships that also define chocolate-tablet boudinage with two perpendicular directions of stretching.

At the microscopic scale, samples of the pluton contain fabrics that indicate magmatic flow within the pluton. Networks of tabular feldspar with interstial quartz and mafic phases define these fabrics. The feldspars are relatively undeformed. However, the feldspars are tiled and form proto C/S fabrics, which suggest a non-coaxial component to the magmatic flow (Gapais, 1989) throughout the pluton. An interesting feature of the kinematics within the Chief Mathew's pluton is that the shear-sense is highly variable throughout the pluton (Fig. 8).

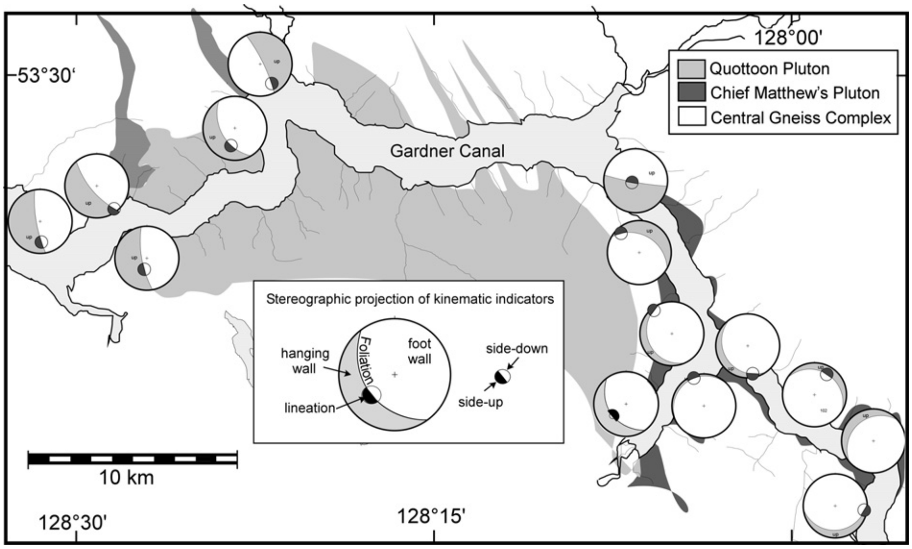

Fig. 8. Map showing distribution of kinematic information using lower-hemisphere, equal-area stereonets for Gardner Canal. The data include outcrop-scale and micro-scale observations of shear sense indicators.

Along the axis of Gardner Canal, the dominant flow direction appears to be NW–SE. In contrast, to the SW in Chief Mathews Bay flow is NE–SW on average. Overall, the geometry of the structures is consistent with intrusion of the sills during sub-vertical shortening and both orogen-parallel and orogen-perpendicular stretching. This overall pattern of deformation is consistent with tectonic extension during emplacement of the sill complex.

3.4. Europa Reach

The rocks at Europa Reach (Figs. 2–5) are amphibolite and orthogneiss metamorphosed in the epidote amphibolite facies. The orthogneiss and amphibolite are characterized by abundant epidote and microcline. Garnet and clinopyroxene are present in the amphibolites. No orthopyroxene is found in the rocks, which constrains the peak temperature to the amphibolite facies. No migmatites were recognized in the area. Microscopically, the rocks show equigranular texture, with polygonal grains with boundaries at 120°. Some biotite grains are enclosed in larger feldspar grains. These textures indicate deformation at high temperatures and recovery after deformation.

The foliations at Europa Reach (S_{ER}, Table 1) strike NW–SE and dip steeply SW. The mineral lineations are clustered with shallow plunges to the S (Fig. 6), consistent with strike-slip deformation. Some outcrops are isoclinally folded (F_{ER}) with axial surfaces that parallel the NW–SE foliation. Fold hinges plunge shallowly to the SE, sub-parallel to the mineral lineations. Parallel to the foliation, layers of calc-silicate rock are stretched into boudins. Sets of conjugate shear-bands are bisected by the foliation plane (Locality 7, Fig. 5) indicating coaxial shortening normal to the foliation (Platt and Vissers, 1980). All the structural elements point to NW–SE stretching and NE–SW shortening. The S_{ER} fabric is crosscut by the Quottoon pluton along the pluton's western side, suggesting deformation here predated emplacement of the pluton.

3.4.1. Kinematics

C′ shear-bands crosscutting the foliation are common. Although conjugate pairs of shear-bands are common (Fig. 6), dextral shear-bands dominate and strike N–S with steep dips to the east. The sinistral set is less developed and strikes NW–SE and is sub-vertical. The dominance of dextral shear-bands together with the shallow lineation indicates a large dextral component to the deformation. Microstructural analyses performed on oriented thin-sections documented sigma clasts, C/S fabrics and C′ structures, and confirm a dextral sense of shear (Fig. 8).

3.5. Autocorrelation function analysis

The structural analysis at Gardner Canal was complemented with results obtained using the autocorrelation function (ACF) technique (Heilbronner, 1992), which uses a Fast Fourier Transform to estimate the average shape that occurs in an image, in this case an oriented thin section. This technique is powerful when applied to plutonic rocks and rocks of the CGC since conventional strain analysis techniques are impossible or hard to apply in these lithologies. Even though the ACF does not measure finite strain, it is used as a means to compare deformation intensities between the rocks. The ACF is a function of grain size, shape and orientation of individual grains and spatial density of mafic versus felsic minerals. The orientation of the mineral grains can be seen in the shape of the ACF. Foliated rocks show elongated patterns parallel to the foliation, while non-foliated rocks show isotropic patterns (Fig. 9). Deformation intensity can be calculated by taking the ratio of the maximum and minimum axes of the ellipse representing a thresholded gray-level contour in the ACF. For consistency, we picked the ellipse representing the 96th gray-level in the image (Fig. 10). The calculated value is a minimum estimate of the true strain, and is independent of the original grain size of the rock. All thin-sections used for this analysis were cut parallel to the lineation and perpendicular to the foliation, and thus should correspond to the X–Z plane of finite strain.

In general, the sizes of the ellipses obtained using the autocorrelation function for the area of Gardner Canal are a function of the rock type. Country-rocks (Fig. 9c) have ellipses that are consistently smaller than the rocks of the Quottoon pluton (Fig. 9b). Smaller ellipses can be correlated with smaller grain size of the rocks, which may indicate grain size reduction. This observation suggests that the plutonic rocks may be less deformed than the country-rocks, again pointing to an intrusion of the Quottoon and Chief Matthew's plutons late in the deformation history of the area. Ellipses were

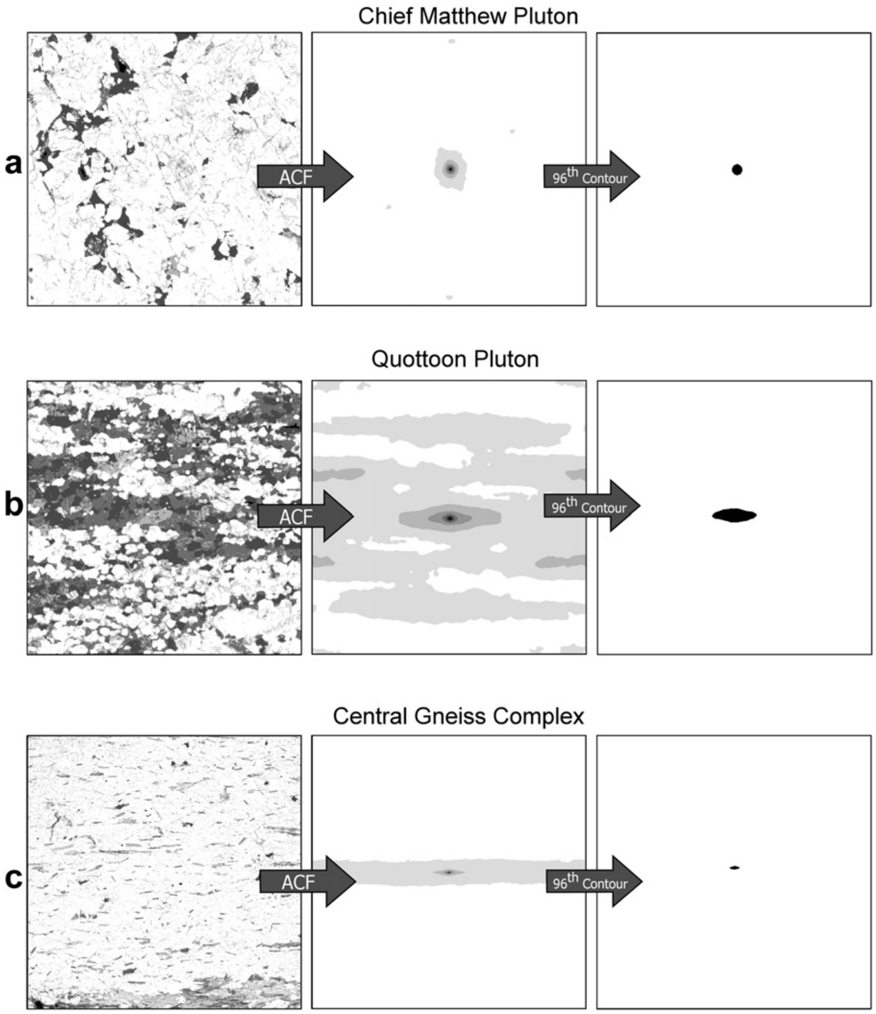

Fig. 9. Examples of autocorrelation function analysis for different lithologies. The first image is a black and white scan of a thin-section; the second image is the autocorrelation function of the thin-section; and the third image is the previous image filtered by selecting only the gray colors greater than the 96th gray level, producing an ellipse that is a measure of deformation intensity. The examples show the effect of a foliation and grain size on the resulting ellipse. a) plutonic rock; b) amphibolite gneiss; and c) biotite gneiss.

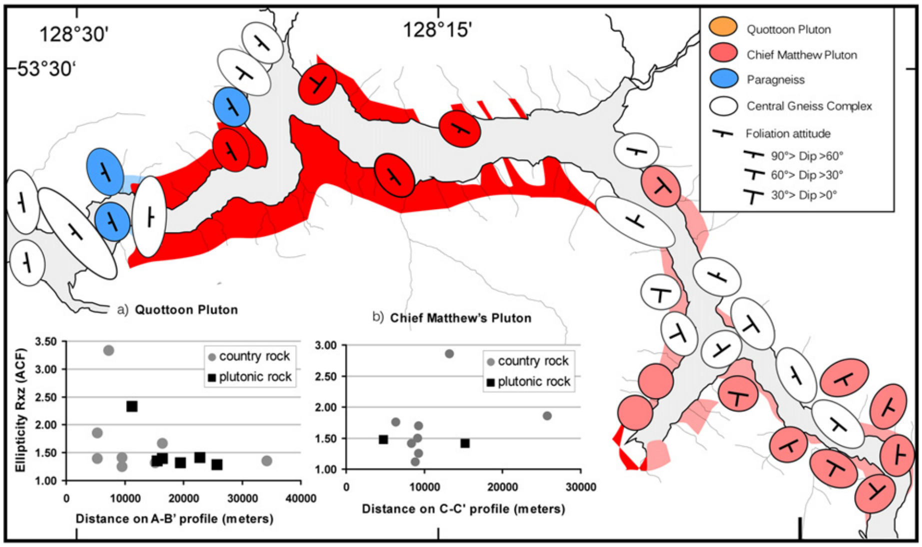

Fig. 10. Map showing the deformation intensity ellipses calculated using the autocorrelation function for individual rocks at Gardner Canal. The size of the ellipses was normalized to the average measured size to ease comparison of orientations and shapes. The ellipses are oriented with respect to the foliations of the rocks. The two graphs compare the ellipticity of the individual measurements along the cross-sections A–A′, B–B′ and C–C′ (Fig. 5). Ellipses were plotted with the long axis parallel to the strike of the local foliation.

normalized to show the same minimum diameter, and to compare the deformation intensities independent of the original grain size (Fig. 10).

The ellipses are oriented with the long axis parallel to the orientation of the foliation for each sample (Fig. 10). The general value for relative magnitudes of deformation intensity obtained for the plutonic rocks of Chief Matthew's pluton is 1.25, and for the Quottoon pluton 1.7. The position of the CSZ at Brim River is highlighted by the NW–SE orientation of the ellipses (Fig. 10); toward the east and west the orientations change. The variable orientation of the ACF ellipses for the Chief Matthew's pluton is consistent the variable pattern of foliation, lineation and shear-bands. Overall the ACF strain ellipses and field measurements are consistent with horizontal flow during sub-vertical flattening and radial stretching during pluton emplacement. At Europa Reach the most prominent calculated strain ellipse shows an orientation for the stretching and shortening directions that matches the one derived by the shear-band analysis, and the ellipticity is 3.33, the largest observed in this study.

4. Discussion

4.1. Coast shear-zone (CSZ)

The CSZ is a crustal scale shear-zone that extends for more than 1200 km (Brew and Ford, 1978; Ingram and Hutton, 1994; Klepeis et al., 1998; Andronicos et al., 1999; Rusmore et al., 2001) from Alaska to British Columbia. The minimum age of this structure is given by the age of the Quottoon pluton, which intruded synkinematically during the waning evolution of the structure (Crawford et al., 1987; Ingram and Hutton, 1994; Klepeis et al., 1998; Andronicos et al., 1999; Rusmore et al., 2001). The CSZ was developed after the accretion of terranes (Chardon et al., 1999), however it may be a reactivated major suture between terranes (Hollister and Andronicos, 1997). The structure was reactivated several times, and left-lateral, dextral, reverse and normal motions were described for different time periods. Along strike (NW–SE), the CSZ is characterized by steep foliations, which usually dip to the NE, and are associated with nearly vertical lineations (Crawford et al., 1987; Ingram and Hutton, 1994; McClelland et al., 1992; Klepeis et al., 1998; Andronicos et al., 1999; Rusmore et al., 2001).

At Gardner Canal Rusmore et al. (2001), placed the CSZ east of Brim River based on the presence of protomylonitic fabrics in the Quottoon pluton, and the presence of reverse shear-bands that strike NW and dip to the NE. We agree with this inferred position for the CSZ but found no evidence for NE dips in the outcrops we visited. As described above, the Quottoon Pluton, east of the CSZ is characterized by a steeply SW dipping solid-state foliation and steeply plunging lineation. Another discrepancy from other localities is that the CSZ is usually associated with E-side-up reverse shear-sense (eg. Ingram and Hutton, 1994). At Gardner Canal, even though we agree with reverse kinematics for the CSZ, the geometry of folds and shear-bands consistently indicate an SW-side-up, top to the NE reverse shear.

At Europa Reach, west of the Quottoon pluton, the absence of migmatite implies the rocks did not Reach temperatures as high as the rocks south and east of Brim River, which are dominated by migmatite. We interpret the lack of migmatite as a clear indication of a contrast in thermal history east and west of the Quottoon pluton, similar to along the CSZ north of Gardner Canal (Crawford et al., 1979, 1987). This contrast in metamorphic history is consistent with the presence of a major structural break across the CSZ, and the rocks to the west as part of the Western metamorphic belt, which did not Reach temperatures as high as those recorded in the CGC (Stowell and Crawford, 2000). The dextral kinematics found at Europa Reach could be older and possibly related to the intrusion of the Butedale pluton at 84 Ma (Gehrels et al., 2009). Alternatively, the dextral kinematics could be related to deformation in the CSZ, as seen at the Skeena River (Andronicos et al., 1999).

The southern continuation of the CSZ is not well defined. The most western location studied within the Kitlope Pluton has foliations that strike N–NW and dip steeply to the east with steeply plunging lineations. NE of this location, foliations change progressively to NS and then EW (Fig. 3). These orientations may indicate a strain rotation on the western side of the Kitlope pluton consistent with the presence of the CSZ. The SW corner of the map (Fig. 3) is along strike with the CSZ west of Brim River (Figs. 2 and 5). However, we have not definitively found the CSZ along the western side of the Kitlope Pluton, suggesting it may be farther west than our present mapping.

4.2. Kinematics of pluton emplacement

The Quottoon, Chief Matthew's, and Kitlope plutons are part of a large magmatic flare-up that took place east of the CSZ from 65 to 50 Ma (Gehrels et al., 2009). Prior to this event, the area was the site of magmatism since the Late Jurassic. Long-lived magmatism modifies the thermal state of the crust, with an enhanced geothermal gradient isothermal down to the Moho (Depine et al., 2008). We argue that the plutons at Gardner Canal were emplaced in crust that was at homogeneously high temperatures east of the CSZ. Supporting evidence for this conclusion is the widespread presence of migmatitic amphibolite and orthogneiss, and relative uniform temperatures ranging from 697 to 773 °C and pressures between 0.75 and 0.65 GPa for the Quottoon pluton, and 0.65 to 0.5 GPa for the Chief Matthew's pluton, which were estimated from thermobarometry (Depine, 2009).

An implication of such a hot crust is that most deformation was focused in the weak deformable CGC (e.g. Hollister and Crawford, 1986; Hollister, 1993). After a sufficient melt fraction formed (~7–10% Rosenberg and Handy, 2005; Brown, 2007), melt started migrating. The transition from melt migration by pervasive flow through the crust to pluton emplacement occurred when the melt focused and collected. One proposed region for melt focusing is crustal-scale shear-zones (Hollister and Crawford, 1986; Ingram and Hutton, 1994; Brown and Solar, 1998). The Quottoon pluton was intruded synkinematically with deformation within the CSZ (Ingram and Hutton, 1994; McClelland et al., 1992; Klepeis et al., 1998; Andronicos et al., 1999; Rusmore et al., 2001; this study). The steeply dipping foliations and lineations along the entire length of the Quottoon pluton from the Alaskan border to our study area implies that the Quottoon pluton represented a vertical conduit for magma flow at the crustal scale.

Melt ascended through the CSZ due to pressure gradients, or overpressure (Robin and Cruden, 1994), creating a feedback between deformation and magmatism (Lissenberg and van Staal, 2006). We interpret the vertical structures associated with the Quottoon pluton as the feeder area for the other plutons east of the CSZ, such as the Chief Matthew's pluton.

At Gardner Canal, the Quottoon intruded syntectonically during horizontal shortening at ~60 Ma, as indicated by the flattening fabrics described above (Fig. 11a). Progressive deformation within the pluton was top-to-the NE reverse shear-sense.

By ~57 Ma when the Chief Matthew's pluton intruded, we interpret that deformation changed from horizontal shortening to horizontal extension (compare Fig. 11a to d). The change in the orientation can be explained by either near-field or far-field stress regimes. The first mechanism is near-field to the plutonic system so that the rotation in the shortening direction only depends on forces related to the emplacement of the pluton. In general, the mechanisms

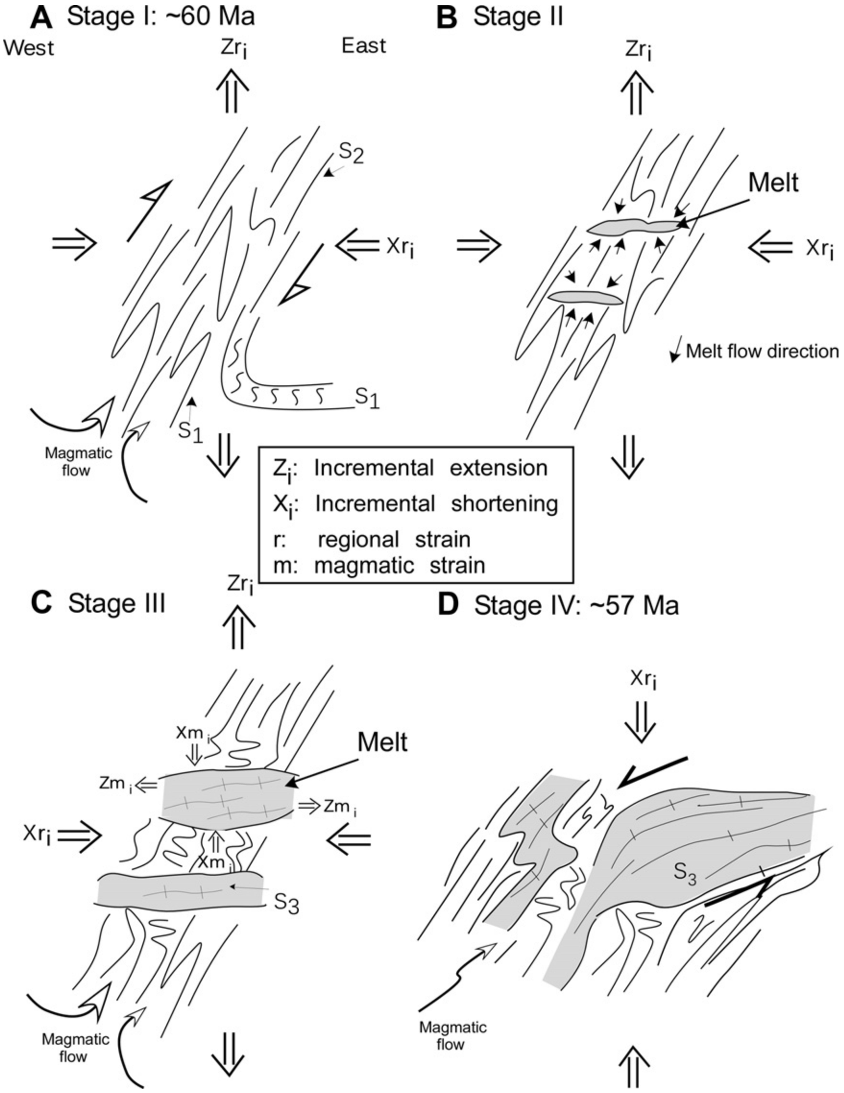

Fig. 11. Sketch of cross-sections for model that shows the transposition of foliation from steeply to shallowly dipping due to melt coalesce and migration during batholith construction. A) Stage 1: Steeply dipping foliation (S_2) developed during transpression overprints a previous foliation (S_1). B) Stage 2: Incipient melt-filled volumes form perpendicular to previous foliation. C) Stage 3: Continuation of melt flow into fractures locally changes the strain axes. D) Stage 4: Melt accumulations form a pluton characterized by horizontal flow and sub-horizontal foliation (S_3).

by which plutons switch from vertical to sub-horizontal are related to buoyancy and to stalling of magma at the brittle/ductile transition (Brown and Solar, 1998). We discount this mechanism because the country-rocks at Gardner Canal deformed ductily, and the amphibolitic migmatites that host the plutons are denser than the plutonic rocks.

A second possible near-field mechanism is hydro-fracturing in the adjacent country-rock during transpression (Davidson et al., 1994; Wagner et al., 2006; Andronicos et al., 2008). This explanation is applied at Gardner Canal based on the following field observations. The Quottoon pluton developed melt-filled tensile fractures oriented perpendicular to the foliation and lineation (Fig. 4c), parallel to the incremental shortening direction during horizontal shortening, and perpendicular to the steeply plunging incremental stretching direction (Fig. 11b). Once formed, sub-horizontal melt-filled fractures perturbed the stress-field creating locally reoriented principle stress directions that allowed a change in the strain geometry (Fig. 11c; Davidson et al., 1994; Andronicos et al., 2008). As magma accumulates in volume, the sill grew in a geometry consistent with the reoriented stress field (Fig. 11c). At this stage, the sills grew parallel to the minimum stress and perpendicular to the maximum stress (Wickham, 1987; Brown and Solar, 1998)(Fig. 11c). The magmas that formed the Chief Matthew's pluton may have grown in this way to produce large pathways for sub-horizontal magmatic flow. This mechanism could explain the horizontal geometry for the Chief Matthew's pluton as well as producing the vertical shortening around the proposed sill complex.

Alternatively, the change in the direction of the shortening during pluton formation and emplacement could be explained by a change in far-field stresses. The Chief Matthew's pluton shows horizontal foliations and horizontal lineations, formed during sub-vertical flattening and radial stretching. These geometries are consistent with intrusion of the pluton in an extensional or trans-tensional regime for an angle of divergence between Kula and North America plates greater than 20° (Teyssier and Tikoff, 1999). Other plutons of the same age in the Coast Mountains show a similar sub-horizontal geometry related to regional extension: i.e.

Khyex sill complex (67–63 Ma; Crawford et al., 1999), Kasiks sill complex (53 Ma; Andronicos et al., 2003), Tsaytis pluton (56 Ma; Van der Heyden, 1989).

Independent of the cause for the transposition of the foliation between 60 and 58 Ma, plutons do perturb the near-field stresses during emplacement (Paterson and Fowler, 1993; Hollister and Crawford, 1986). The rocks around the Chief Matthew's pluton preserve several synplutonic structures that exemplify this fact, including extensional shear-bands with different orientations, isoclinal folds, chocolate-tablet boudinage, and areas of extreme stretching. These structures indicate that the deformation was partitioned within the country-rocks to create room for the intrusion. The almost perpendicular poles to shear-bands indicate that overall the pluton intruded during vertical flattening, but the deformation was partitioned into domains of flattening, stretching and simple-shear. So, when several plutons occur in an area, the regional strain field is also affected, and the question remains how much can we infer about far-field tectonics of an area based on the study of plutons?

4.3. Using plutons to infer tectonic plate regimes

Three different tectonic models, based on plate reconstructions, have been proposed for the North American margin during the Late Cretaceous and Paleogene. The first one relies on a change in the convergence angle of the Kula-Pacific plate from orthogonal to more oblique at ∼55 Ma (Lonsdale, 1988). This triggered orogenic collapse, exhumation of high-grade rocks, and increased magmatism due to decompression (Lonsdale, 1988; Struik, 1993; Andronicos et al., 2003). The second model proposed the existence of an extra, now-fully subducted, plate called the Resurrection plate (Haeussler et al., 2003) that generated extensional exhumation of the middle crust, and a magmatic flare-up possibly related to a slab-window. The third model, based on paleomagnetic data, states that a large segment of western North America was translated more than 3000 km northward in the middle Cretaceous and finally docked to the present position at ∼50 Ma (Beck, 1976; Irving et al., 1985). The CSZ was proposed to be the structure where this strike-slip displacement (ca 1000 km) occurred (Irving et al., 1996; Hollister and Andronicos, 1997). This model is not exclusive of the first one.

If we assume that the orientation of the plutons in the study area is purely an expression of the relative convergence direction between the Kula and Pacific Plates, then, following the first two regional models for plutons older than ∼57 Ma, we should expect to find kinematic evidence reflecting NE–SW shortening, and plutons younger than ∼56 Ma should indicate extension. Also, if we consider the third model, the structures of plutons older than ∼50 Ma and associated with the CSZ (e.g. Quottoon and Kitlope plutons) should show evidence of large dextral displacement.

The Quottoon Pluton at Gardner Canal shows NE–SW shortening, which would be consistent with the pluton intruding during dextral transpression (Fig. 12). However, the kinematic indicators show top-to-the NE reverse shear, which indicate that the intrusion of the Quottoon pluton was late in the area, after the strike-slip displacement ended, as was proposed for the Quottoon pluton at the Skeena River (Andronicos et al., 1999). The dextral kinematic indicators contained within the S_{er} fabric found west of and crosscut by the Quottoon Pluton at Europa Reach are evidence for dextral displacements either prior to, or by partitioning of the strain during, the intrusion of the Quottoon pluton. The Kitlope pluton is dominated by E–W striking foliations and shear-bands dominated by sinistral shear, that can be interpreted to be antithetic to dextral shearing across the NW striking CSZ (Fig. 12).

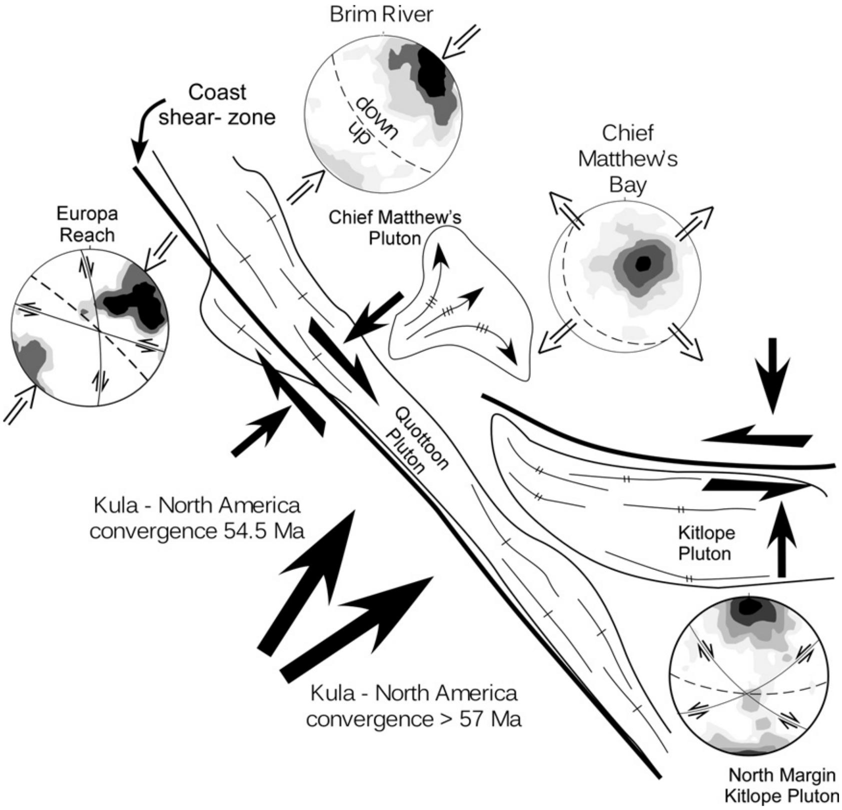

Fig. 12. Schematic map view showing the orientations of the Quottoon, Kitlope, and Chief Matthew's plutons. Also shown are summary stereonets showing average shear-band orientations and contours to poles for foliation. Plate convergence vectors between Kula and North American plates for 57 and 54.5 Ma are shown (Lonsdale, 1988).

The Chief Matthew's pluton is characterized by vertical flattening, and it is linked to extension. This pluton matches regional models that argue for a change from shortening to extension. Crawford et al. (1999) also reported the transition from shortening to extension at 59 Ma for the CGC north of the Skeena River, based on studies on the Khyex sill complex, which is located south of Portland Inlet. Other areas that experienced tectonic extension in the Canadian Cordillera are located in the Omineca belt, which is characterized by a series of metamorphic core complexes, bounded by extensional detachment faults, and exhumed during an increase in Eocene magmatic activity (Ewing, 1980; Struik, 1993). The switch from a contractional to extensional regime is also reported at ~58 Ma for the Omineca belt (Parrish et al., 1988; Parrish, 1995; Vanderhaeghe et al., 2003).

Mahoney et al. (2009) argued that the cause of extensional deformation within the Coast Mountains was related to delamination of dense lower-crustal material, formed as a result of differentiating plutons. The removal of this dense material and its replacement by hot buoyant asthenosphere would result in extension and increased magmatism. Extensional deformation affected much of the Cordillera during the early Eocene, including areas as far south as Washington and Idaho, and as far north as the southern Yukon, as well as major portions of the Coast Mountains (eg. Andronicos et al., 2003). The areal extent of this extensional event makes it likely that if delamination did occur, it happened in concert with plate margin processes, which are the only processes we believe could have affected such a large area synchronously.

Our observations indicate that far-field tectonic processes are recorded by the patterns of deformation within the plutons at Gardner Canal. However, a strong interplay occurred between near-field processes related to pluton intrusion and growth, and far-field tectonic changes occurring within the Coast Mountains between the late Paleocene and Early Eocene.

5. Conclusions

The structural analysis of three middle-crustal plutons (Kitlope, Quottoon, and Chief Matthew's plutons) that were emplaced during a time span of ~6 Ma in the Coast Mountains, and show different finite strain patterns, provide insight into strain partitioning, pluton emplacement mechanisms and the role of melt during orogenesis.

These plutons intruded during the time interval when a transition from contraction to extension occurred across the Cordillera as recorded in Late Cretaceous–Early Cenozoic metamorphic core complexes. We found that there was a change from horizontal to vertical shortening between the emplacement of the Quottoon and the Chief Matthew's plutons between 60 and 57 Ma. This transition likely reflects both near-field deformation, produced by the transport and emplacement of magmas, and far-field plate margin processes.

We present a model to explain the kinematics of how the transposition of fabrics occurred. Horizontal tensile melt-filled fractures developed perpendicular to the Quottoon pluton's foliation consistent with the orientation of the regional horizontal shortening strain. As the melt-filled fractures became larger, they changed the orientation of local strain axes, which encouraged sub-horizontal melt flow that formed a gently dipping batholith over time.

The strain and inflation produced by the intrusion of the well-exposed Chief Matthew's pluton was partitioned into coaxial and non-coaxial domains. Altogether, the different domains and the lineation orientation with respect to the foliation indicate radial flow of the magma during intrusion and vertical flattening linked to sill-growth. This pattern of deformation is most consistent with regional tectonic extension during emplacement of the Chief Mathew's pluton.

Acknowledgments

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